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Rainfall Retention Probabilities Computed for Different Cropping–Tillage Systems

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ABSTRACT

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Rainfall and runoff event data from several different cropping and tillage systems on three field-sized watersheds in the Southern Piedmont of the U.S.A. are used to estimate empirical probability distributions of the USDA Soil Conservation Service runoff curve number. Long-term rainfall records from a nearby gauge are also employed to obtain probabilities for rainfall event occurrence and depth. These probability distributions of runoff curve number and rainfall occurrence and depth are incorporated in a recursive computer procedure to compute estimated probability distributions of annual rainfall retention for the different cropping-tillage systems. Comparison of these estimated rainfall retention probability distributions shows a reduction in the risk for low rainfall retention with the installation of conservation tillage systems.

INTRODUCTION

A portion of the rain that falls on cropland during a rainfall event does not run off, but is retained by vegetative cover and soil. This retained rainfall provides water for evapotranspiration and is needed for crop production. If an insufficient amount of rainfall is retained, crops will either suffer from drought or supplemental irrigation will have to be provided. The amount of rainfall retained during an event is strongly influenced by both the total amount of rain falling and the storage capacity of the vegetation and soil at the beginning of the event. These quantities, as well as other factors that affect retention, such as rainfall intensity, are highly variable and can only be predicted on a long-term basis in probabilistic terms. Thus, to evaluate quantitatively the effects of different cropping–tillage systems on rainfall retention under future

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uncertain rainfall conditions, it is desirable to obtain rainfall retention probabilities rather than one predicted amount of retention for each system.

To obtain rainfall retention probabilities directly from data would require the collection of rainfall and runoff data from a number of cropping–tillage systems over a long period of time. This is clearly not feasible because of the cost and time delay; thus, short-term data on rainfall and runoff must be coupled with nearby long-term rainfall data to compute rainfall retention probabilities for different cropping–tillage systems.

Event data on rainfall and runoff have been collected from three field-sized watersheds under a number of different cropping–tillage systems in the Southern Piedmont of the U.S.A. for periods ranging from 1 to 4 years. This paper describes how these short-term data were coupled with a 34-year rainfall record from a nearby gauge to obtain estimated probability distributions of rainfall retention for the different cropping–tillage systems. These estimated probability distributions are compared to examine the effects of different cropping–tillage systems on rainfall retention probabilities for Southern Piedmont fields.

DATA AND METHODS

Runoff model parameters

The three field-sized research watersheds from which rainfall and runoff data were collected for this study were previously described by Smith et al. (1978), Langdale et al. (1979, 1985), Thomas et al. (1982) and Mills et al. 91986). Cropping–tillage systems that were in effect on the watersheds during the study are given in Table 1.

Data on rainfall and runoff for individual events on the research watersheds were used to compute curve numbers, which are parameters, for the USDA Soil Conservation Service (SCS) runoff model (USDA Soil Conservation Service, 1972). The SCS runoff model is expressed by the following equations:

$$Q=\frac{(P-I)^2}{(P-I)+S} \qquad P\geq I \tag{1}$$

$$Q=0 \qquad P\leq I \tag{2}$$

$$I=0.2S \tag{3}$$

$$S=2.54\left(\frac{1000}{N}-10\right) \tag{4}$$

where Q is runoff volume (cm of depth over the watershed); P rainfall depth (cm); I initial abstraction (cm); S watershed storage (cm); and N the runoff curve number.

The curve numbers computed with the above equations using rainfall and

TABLE 1

Cropping–tillage systems on three research watersheds in the Southern Piedmont, U.S.A.

Watershed	System number	Period in effect	Summer crop	Winter crop	Tillage	Implement
P1	1	1-10-72 to 21-10-74	Soybeans	None	Conventional	Disk harrow
	2	22-10-74 to 1-10-76	Grain sorghum	Barley	Conservation	Fluted coulter
	3	5-11-76 to 7-11-80	Soybeans	Wheat	Conservation	Coulter inrow chisel
	4	8-11-80 to 13-10-82	Grain sorghum	Clover	Conservation	Coulter inrow chisel
P3	5	4-12-72 to 5-11-75	Soybeans	Rye, Barley	Conventional	Disk harrow
	6	6-11-75 to 5-11-78	Grain sorghum	Barley, Wheat	Conservation	Fluted coulter
	7	6-11-78 to 7-11-79	None	Wheat, Rye grass	None	None
	8	8-11-79 to 9-11-82	Soybeans	Wheat	Conservation	Coulter inrow chisel
P4	9	2-11-73 to 5-11-75	Corn	Rye	Conventional	Disk harrow
	10	6-11-75 to 5-11-78	Soybeans	Barley, Wheat	Conservation	Fluted coulter
	11	6-11-78 to 7-11-79	None*	Wheat, Rye grass	None	None
	12	8-11-79 to 10-11-82	Soybeans	Wheat	Conventional	Disk harrow

*Terraces reconstructed during summer.

runoff data were found to vary widely for different events on each of the watersheds and cropping–tillage systems. Table 2 gives the maximums, minimums, and averages. The highest curve number of 98.03 for cropping–tillage system 1 represents a runoff condition equivalent to that of a paved parking lot (USDA Soil Conservation Service, 1975). The watershed was probably in a wet condition at the time of occurrence of this event. The lowest curve number of 38.54, which was obtained from an event on P1 with cropping–tillage system 2, indicates a runoff condition slightly better than that of a pasture or range with good cover in a dry condition (USDA Soil Conservation Service, 1972).

Although actual watershed conditions were not recorded for individual events, much of the variation in curve numbers may reasonably be attributed to differences in antecedent moisture conditions. Variation in curve numbers among events for a cropping–tillage system may also be due in part to variation in vegetative cover during the year. Other sources of curve number variation could be errors due to rainfall intensity variations which the SCS model does not handle.

Because the runoff curve numbers varied widely even for the same watershed and cropping–tillage system, it was desired to obtain a curve number probability distribution for each cropping–tillage system on each watershed. Such probability distributions provide stochastic models of watershed state. For this study, the watershed state models were obtained by computing empirical probability distributions of the curve number samples for each watershed and cropping–tillage system. This was accomplished by assigning an equal fraction of the total probability of one to each curve number value computed from runoff event data for a specific watershed and cropping–tillage system. With this assignment of probability, the cumulative empirical distribution function of the curve number samples jumps an equal amount at each sample because probability mass is concentrated equally at the curve number sample points. As an

TABLE 2

Maximums, minimums and averages of SCS runoff curve numbers obtained for research watersheds

	Watershed											
	P1				P3				P4			
	Cropping-Tillage System				Cropping-Tillage System				Cropping-Tillage System			
	1	2	3	4	5	6	7	8	9	10	11	12
Max.	98.03	90.26	86.71	54.43	94.95	89.44	88.08	86.01	91.91	85.78	86.46	89.44
Min.	44.25	38.54	42.76	40.92	42.40	44.25	52.48	41.03	48.94	44.25	64.03	44.03
Av.	80.33	71.92	65.37	51.99	76.99	68.93	75.94	63.91	76.03	67.60	79.89	73.36

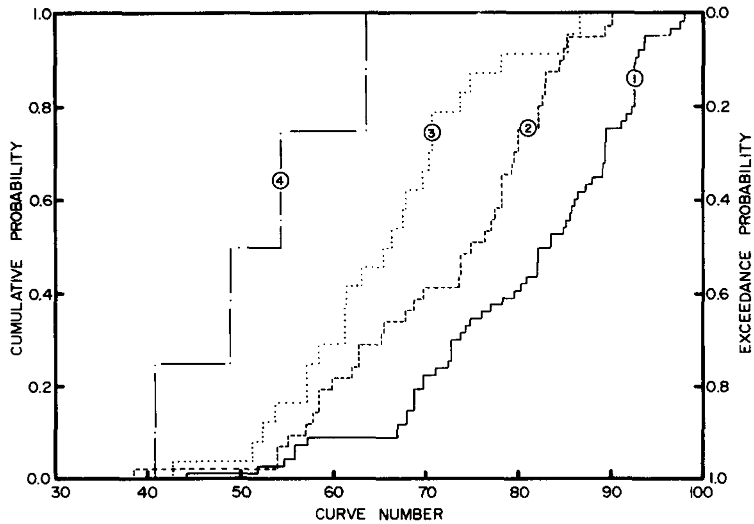

Fig. 1. Empirical probability distributions of runoff curve numbers for cropping–tillage systems 1, 2, 3, and 4 on watershed P1.

example, the cumulative empirical probability distributions of curve numbers computed for the cropping–tillage systems on watershed P1 are given in Fig. 1.

It should be pointed out that the curve number empirical probability distributions may show slightly greater estimated probabilities than actual for the higher curve numbers. This is because only rainfall events with runoff were used in the computation of runoff curve numbers. Rainfall events producing runoff are more likely to have higher curve numbers than the total population of rainfall events. Many rainfall events will produce no runoff because a large rainfall is required to produce runoff when curve numbers are low. Thus, the sample of curve numbers obtained for each cropping–tillage system in this study contains a possible upward bias. When the empirical probability distributions are used as stochastic state models for computing rainfall retention probabilities, the possible bias in estimated curve number probabilities can result in estimated rainfall retention probability distributions that give slightly higher probabilities for the lower amounts of rainfall retention. Further discussion of this possible bias is continued in a later section where rainfall retention probability distributions are compared.

Rainfall model

For coupling the short-term data on rainfall and runoff from the three research watersheds to a 34-year (1945–78) rainfall record from a nearby rain gauge, a stochastic rainfall model constructed from the long-term rainfall data was used.

This stochastic model, which was that previously employed in estimating soil loss probabilities (Mills et al., 1986), included both rainfall event occurrence and rainfall depth. For rainfall event occurrence, the Poisson process model was used. This model has been found to be appropriate for many locations (Fogel and Duckstein, 1969; Todorovic and Yevjevich, 1969; Fogel et al., 1971; Duckstein et al., 1972; Duckstein et al., 1979; Mills, 1982; Mills et al., 1986). The Poisson parameter, which is the expected rate of event occurrence, was estimated from the 34-year rainfall record as 9.92 events per year.

For rainfall event depth, the Weibull probability distribution was employed. The Weibull density function expressed in a form suggested by Cohen (1965) is:

$$f(x) = (\gamma/\theta)x^{\gamma-1}\exp(-x^{\gamma}/\theta) \tag{5}$$

where x is event rainfall depth, and γ and θ are model parameters. The Weibull cumulative distribution is given by the equation:

$$F(x) = 1 - \exp(-x^{\gamma}/\theta) \tag{6}$$

Estimates of the Weibull parameters γ and θ from the 34-year rainfall record were 0.793 and 40.4, respectively. For these computations rainfall depth was expressed in tenths of mm.

Computational method

Estimated rainfall retention probability distributions for the different cropping–tillage systems were computed by coupling the stochastic state model (empirical probability distribution of SCS runoff curve numbers) obtained from the short-term data for each system with the stochastic rainfall model obtained from the 34-year rainfall record. For this coupling, a computer procedure incorporating a recursive technique derived through the use of generating functions (Mills, 1980) was employed. This procedure is similar to those used by Mills (1981) in deriving sediment yield probability distributions for Ahoskie Creek watershed in North Carolina, and by Mills et al. (1986) to obtain estimated soil loss probability distributions for the cropping–tillage systems on the Watkinsville watersheds.

The recursive technique incorporated in the computer procedure provides a discrete probability mass function for class intervals of cumulative amount of rainfall retained for a specified period, such as a year. This probability mass function is then summed to obtain a cumulative probability distribution. The recursive technique consists of the following two equations:

$$u_0 = \exp(-\beta + b_0) \tag{7}$$

$$u_k = \frac{1}{k}\sum_{j=1}^{k} j b_j u_{(k-j)} \tag{8}$$

where u_0 is the probability of having no rainfall retained during the specified period of concern; and u_k, for $k=1, 2, 3, ...$, the probability of having a cumulative amount of rainfall retained in rainfall retention class interval k for the period of concern. The parameter β is the expected number of rainfall events during the period of concern, and the parameters b_j, for $j=0, 1, 2, ...$, are obtained from the equation:

$$b_j = \sum_{i=1}^{m} \beta_i q_{ij} \tag{9}$$

where β_i is the expected number of rainfall events with depth in rainfall event depth class interval i, for $i=1, 2, 3, ..., m$, and is computed by multiplying the total expected number of rainfall events for the period of concern by the probability of an event having rainfall depth in rainfall depth class i. This probability is obtained from the Weibull probability model for rainfall event depth given in the previous section. The number m of rainfall event depth classes is chosen so that the probability of exceeding class m is extremely small. In this study 200 classes were used with an exceedence probability less than 2.0×10^{-5}.

The quantities q_{ij} in equation (9) are the probabilities for individual event rainfall retention in class j given event rainfall depth in class i, for $i=1, 2, 3, ..., m$, and $j=0, 1, 2, ...$ These probabilities are obtained by summing estimated probabilities for curve numbers that give event rainfall retention in class j for rainfall event depth in class i. The estimated curve number probabilities are obtained from the empirical distribution of curve numbers computed for each cropping–tillage system as described previously. A deterministic transform model that provides amount of event rainfall retention for given rainfall depth and a given value for the SCS curve number is also used in the computations. This deterministic transform model employs the SCS runoff model to provide event runoff as the complement of rainfall retention.

RESULTS AND DISCUSSION

Estimated probability distributions of annual amount of rainfall retention computed for the different watersheds and cropping–tillage systems with the computer procedure are given as Figs. 2, 3 and 4. These figures show some differences between estimated rainfall retention probability distributions for different cropping–tillage systems. The estimated rainfall retention probability distribution for cropping–tillage system 1 (Fig. 2), which is conventionally tilled soybeans with no winter crop and no grassed waterway on watershed P1, indicates a higher probability for having a low amount of annual rainfall retention than the estimated probability distributions for conservation cropping–tillage systems 2, 3 and 4. There also appears to be a decrease in the probability for having a low amount of rainfall retention with successive con-

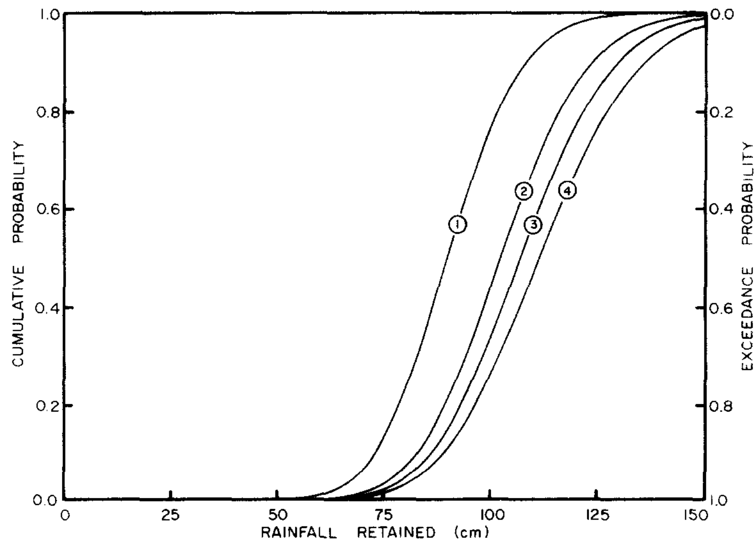

Fig. 2. Probability distributions of annual amount of rainfall retention for cropping-tillage systems 1, 2, 3, and 4.

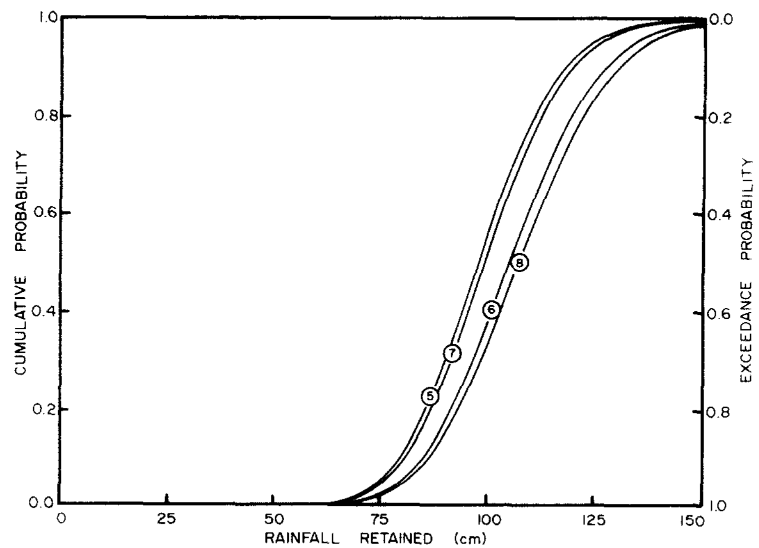

Fig. 3. Probability distributions of annual amount of rainfall retention for cropping-tillage systems 5, 6, 7, and 8.

servation cropping-tillage systems 2, 3 and 4. This progressive improvement in rainfall retention is attributed to a buildup of surface residue and improved soil tilth, which greatly increases infiltration and other factors affecting capture of rainfall.

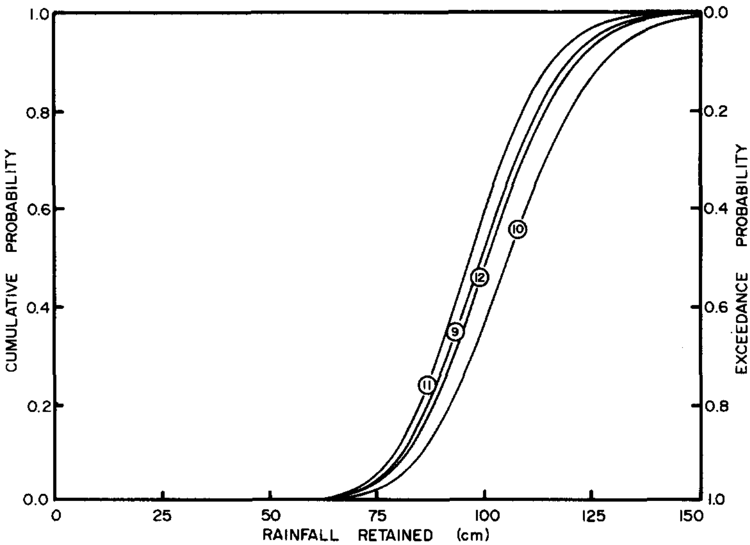

Fig. 4. Probability distributions of annual amount of rainfall retention for cropping-tillage systems 9, 10, 11, and 12.

Estimated probability distributions of annual rainfall retention for watershed P3 (Fig. 3) also show higher probabilities for having low amounts of rainfall retention for conventional tillage system 5 than for conservation cropping–tillage systems 6 and 8. The estimated rainfall retention probability distribution for system 7, which consists of a winter crop of wheat and rye grass baled for hay followed by no crop and no tillage during the summer, indicates probabilities for rainfall retention close to those for conventional tillage system 5. The effect of system 7 on rainfall retention is, therefore, quite different from its effect on soil loss. As previously reported (Mills et al., 1986), the soil loss estimated probability distribution for system 7 is similar to those of conservation cropping–tillage systems 6 and 8 and quite different from the estimated soil loss distribution for conventional tillage system 5. Thus, system 7 seems to be very effective in retaining soil, but less effective in retaining water.

The estimated rainfall retention probability distributions for watershed P4 (Fig. 4) indicate higher probabilities for having low amounts of rainfall retention for conventional tillage systems 9 and 12 for conservation tillage system 10. Also system 11, which is a winter crop of wheat and rye grass baled for hay followed by no crop and no tillage during the summer except for terrace reconstruction, appears to retain less rainfall than conservation system 10 and slightly less than conventional tillage systems 9 and 12. Since it was previously observed (Mills et al., 1986) that the estimated annual soil loss probability distribution for system 11 is similar to the estimated soil loss distribution for conservation system 10, it appears that system 11, which is similar to system 7 on P3, is also quite effective in retaining soil, but not water.

The possible bias in estimated curve number probabilities, mentioned in a previous section, that possibly causes a bias in the estimated rainfall retention probability distributions does not preclude using these distributions for comparative purposes. This possible bias would be in all distributions; thus, the differences among distributions would not be significantly affected. When using the estimated rainfall retention distributions for evaluating risks of having insufficiently low amounts of rainfall retention, the distributions can be considered as including 'safety factors' because the possible bias is such that slightly higher probabilities would be given for the lower rainfall retention amounts.

The specific results from this study apply only to field-sized watersheds similar to those used in the study. The general results, however, should be useful in evaluating rainfall retention risks and cropping–tillage systems for other situations. Moreover, the methods and techniques employed in the study can be used for any location where the appropriate data are available.

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